The FSF Post Processing Toolbox User Guide

Post processing spectral data in MATLAB

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1. Introduction

The Field Spectroscopy Facility (FSF) Post Processing Toolbox is a MATLAB toolbox containing functions for importing optical spectra from field-portable specroradiometers and processing them. MATLAB is a computer environment and high-level programming language which provides a flexible environment for processing spectra as well as a good set of built-in data structures, functions and plotting tools. This toolbox is designed as an add-on to MATLAB which will make it easier to import, examine and process data related to field spectroscopy.

Spectra acquired in the field must be post processed to plot and examine spectra, remove invalid data and apply equipment calibrations. MATLAB provides an ideal environment for all these functions, as it provides a flexible environment and set of tools for importing, plotting, analysing and processing data. This toolbox is designed to make the handling of field spectra easier. It provides a number of functions to import the data file formats used by various instrument manufacturers including:

- FieldSpec spectroradiometers manufactured by Analytical Spectral Devices (ASD)
- The GER 1500, GER 3700 and HR-1024 manufactured by Spectra Vista Corporation (SVC)
- The OOI binary file format used by Ocean Optics SpectraSuite software
- The V–SWIR data file format used by the Field Spectroscopy Facility (FSF)

Once imported into MATLAB these data can readily be plotted or further processed. This toolbox provides the following convenient processing functions to:

- **Remove overlapped** spectral data occuring at the join between different detectors
- Sort and **pair** target spectra with corresponding reference spectra using a logsheet file
- Calculate a **relative reflectance** spectrum from paired target and reference spectra
- Calculate an **absolute reflectance** spectrum using calibration data for a reflectance panel
- Remove erroneous spectral data caused by high absorption in the **water bands**
- Smooth spectra with a **Savitzky–Golay** filter
- **Convolve** spectra to the spectral response function (bands) of airborne and satellite instruments

This document exlpains how to install the toolbox, how to handle and plot spectral data using MATLAB structures and how to use the provided processing functions.

1.1. Contributor information and the User Group

This toolbox was developed by Iain Robinson and Alasdair Mac Arthur at the Field Spectroscopy Facility in Edinburgh. This work was supported by the Natural Environment Research Council.

Some features of the function to read ASD binary files were based on code contributed by Andreas Hueni from University of Zürich.

Spectral response functions for a number of satellite sensors was provided by Tim Malthus. Guillaume Drolet, Julia McMorrow, Elizabeth Lowe and Reno Choi provided useful discussion about the convolution of spectral data with the spectral response functions of airborne instruments.

Appendix B on using ViewSpec Pro was written by Peter Walker and Chris MacLellan.

The Field Spectroscopy Facility's User Group provides a selection of useful utilities and tools for the handling and processing of field spectra. We welcome all contributions whether based around MATLAB or other platforms. Please contat us if you have any questions or would like to contribute a resource.

1.2. Further information

An overview of field spectroscopy can be found in the recent review article by Milton [1]. A broad list of references is available from the Field Spectroscopy Facility's web site. A description of MATLAB is available from The MathWorks.

2. Installing the toolbox

This section describes how to install the toolbox on a system running MATLAB.

2.1. Check requirements

The toolbox requires MATLAB 7.8 (R2009a) or later, although some functions may work with earlier versions. The Savitzky–Golay smooth function (`sgsmooth`) additionally requires the Signal Processing Toolbox.

For handling files from Analytical Spectral Devices (ASD) instruments ViewSpec Pro is recommended to convert ASD's binary format to the more easily-readible text format.

Calculation of absolute reflectance requires calibration data for the reference panel which was used in the field. Calculation of radiometric spectra (radiance or irradiance) requires calibration data for the specific instrument and configuration which was used.

> Calibration data for the Field Spectroscopy Facility's reference panels and instruments is available.

Convolution of field spectra to the spectral response functions of airborne or satellite instruments requires the band data for the specific instrument. Data for a range of instruments are available from the User Group.

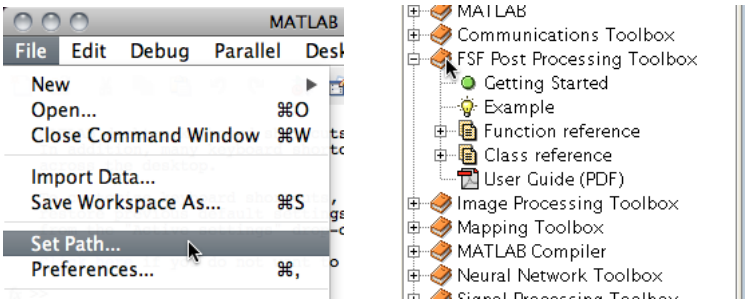


Figure 1: Add the directory containing the toolbox to the MATLAB search path. Additional documentation for the toolbox will appear in the help broswer.

2.2. Download and install

To install the toolbox first download and unzip the file, then add it to the MATLAB search path:

1. Download `FSFPostProcessing1.3.6.zip`.

This zip file contains a folder called `FSFPostProcessing1.3.6` which contains all the functions, documentation and examples in the toolbox.

2. Unzip the file in a folder which is accessible to MATLAB. (If MATLAB is running on a server the toolbox files may need to be located on the server.)

3. In MATLAB: add the `FSFPostProcessing1.3.6` folder to the search path. This can be done using the SET PATH tool which can be opened from the FILE menu, as shown in Figure 1. Click Add folder, then locate the `FSFPostProcessing1.3.6` folder. In order to have MATLAB remember this new path, click SAVE before closing the SET PATH tool.

Once the toolbox is added to the search path the toolbox documentation will appear in the HELP BROWSER under 'FSF Post Processing Toolbox' as shown in Figure 1. Further information about MATLAB's file locations and the search path is available in the MATLAB documentation.

3. Importing, examining and plotting

Once installed spectra acquired on field-portable spectroradiometers can easily be imported from the data file into the workspace. This section describes how to import the files and how to examine and plot the data in the MATLAB environment.

Reliable metadata is critical for field spectroscopy. All instrument data files contain important information in the file's *header*. This includes details such as the date and time the spectrum was recorded, the location it was recorded (for instruments with GPS) and the instrument settings. The toolbox imports this information into a MATLAB structure, along with the data itself.

A few example data files are provided with the toolbox to test these functions. These can be found in the `examples` folder which is located within the folder where the toolbox was installed (`FSFPostProcessing1.3.0/examples`).

3.1. Importing spectral data files

Each instrument manufacturer uses a different data file format for field spectra. A separate import function is provided for each and they are described in the following subsections.

3.1.1. Analytical Spectral Devices (ASD)

Files from ASD FieldSpec 3 and FieldSpec Pro spectroradiometers use a binary format which must first be converted to text files using ViewSpec Pro[1]. This tool is available from ASD's Support Central web site. At the time of writing the latest version was 5.6.10. The procedure to convert binary files to (ASCII) text is described in Appendix B.

An ASD text file can be imported into MATLAB by typing:

```
s = importasd('filename')
```

where `filename` is the name of the file to be imported. Multiple files can be imported at once using wildcards. For example, if the current directory contains several ASD text files with the `.txt` extension they can be imported by typing

```
s = importasd('*.txt')
```

The imported spectrum or spectra will be stored in a structure array in the workspace. If output is not suppressed (with a terminal semi-colon) a struct array will be shown:

```
s =

96x1 struct array with fields:

    name
    datetime
    header
    wavelength
    data
```

The type of data imported (into `s.data`) depends on the operating mode of the ASD spectroradiometer. If the spectra were recorded in *white reference mode* the data values will be reflectances (in the range 0–1) and further processing can continue. If the data were recorded in *raw mode*[2], the spectra must be sorted into reference and target spectra before reflectance can be calculated. This process is described later.

3.1.2. Spectra Vista Corporation (SVC)

Files from SVC spectroradiometers (GER 1500, GER 3700 and HR-1024) are stored in the *signature* text file format[2]. These files usually have a `.sig` extension. Each file contains a header followed by a pair of spectra: one target spectrum and its corresponding reference spectrum.

A SVC signature file can be imported by typing:

[1] This toolbox has very limited support for ASD's binary file format so conversion from binary to (ASCII) text is recommended.

[2] The `importasd` function automatically normalizes data recorded in raw mode to account different integration time settings on different detectors. The normalization method is described in detail in Appendix A.

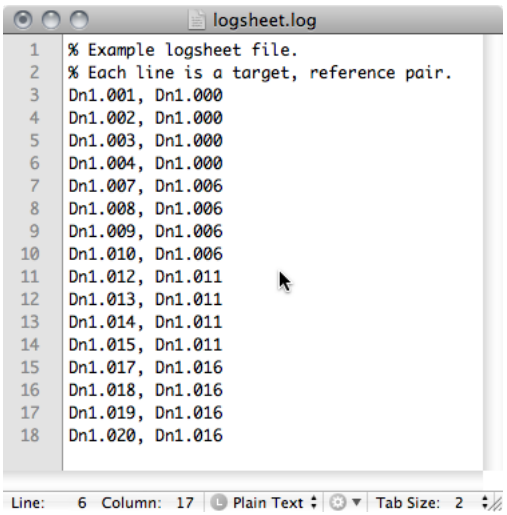


Figure 2: Spectral data recorded in raw mode can be paired by creating a logsheet file.

```
[tar, ref] = importsvc('filename')
```

where `filename` is the name of the file to be imported. Multiple files can be imported at once using wildcards. For example, if the current directory contains several SVC text files with the `.sig` extension they can be imported by typing:

```
[tar, ref] = importsvc('*.sig')
```

The imported spectrum or spectra will be stored in two separate structure arrays in the workspace, one of target spectra (`tar`) and one of reference spectra (`ref`). If output is not suppressed (with a terminal semi-colon) the structures will be shown:

```
tar =

1x7 struct array with fields:

    name
    datetime
    header
    pair
    wavelength
    data

ref =

1x7 struct array with fields:

    name
    datetime
    header
    wavelength
    data
```

Note that the structure array of reference spectra (`ref`) may contain duplicates. This is because signature files always contain the previously-recorded reference spectrum for each target spectrum. Additionally the structure array of target spectra (`tar`) contains a field called `pair`. The value of the pair field gives the name of its corresponding reference spectrum. This pairing information, which matches target spectra to their reference spectra, is required for calculating reflectance.

When importing spectra from SVC instrument models with multiple detectors, such as the HR-1024, there may be overlapped data in the spectra. This occurs at the joins between the different detectors. The `removeoverlap` function, described in Section 4.2, can remove these data.

3.1.3. Field Spectroscopy Facility (FSF)

The FSF has developed a portable spectroradiometer called the Visible Short-wave Infrared (V–SWIR) Spectroradiometer [3, 4]. The function `importvswir` imports data files in the format [5] used by the instrument. V–SWIR data files usually have a `.DTA` extension.

A V–SWIR data file can be imported by typing:

```
[upwelling, downwelling] = importvswir('filename')
```

where `filename` is the name of the file to be imported. Multiple files can be imported at once using wildcards. For example, if the current directory contains several V–SWIR data files with the `.DTA` extension they can be imported by typing:

```
[upwelling, downwelling] = importvswir('*.DTA')
```

The imported structure arrays contain upwelling and their corresponding downwelling spectra. If output is not suppressed (with a terminal semi-colon) then the structure arrays will be displayed:

```
upweling =

1x100 struct array with fields:

    name
    datetime
    header
    pair
    processing
    wavelength
    data

downwelling =

1x100 struct array with fields:

    name
    datetime
    header
    processing
    wavelength
    data
```

The V–SWIR instrument records a downwelling (reference) spectrum for every upwelling (target) sectrum. There will therefore always be the same number of upwelling and downwelling spectra. The `importvswir` function does some basic processing of the spectra, such as dark subtraction, automatically. The field `processing` contains the raw (unprocessed) data.

> For the V–SWIR instrument radiometric calibration data are available from the FSF. These should should be applied before calculating reflectance.

3.2. Examining headers and data

Imported data are stored in MATLAB structure arrays. This ensures that header information (metadata) is kept together with the spectrum itself (wavelength and data). The structure of the data and the ways to examine it are described in the following subsections.

3.2.1. Structure arrays

The spectra are stored in a MATLAB data type called a structure array. A single spectrum is a single *structure*, whereas multiple spectra are grouped together, and numbered, in a *structure array*. The structure is divided into *fields* which contain individual pieces of data. A spectrum structure typically contains the following fields:

- `name` is the name of the spectrum (usually taken from the filename during importing)
- `datetime` is the date and time the spectrum was recorded[3].
- `header` is a structure containing all the header information (metadata) from the original file.
- `pair` appears only in target spectra and gives the name of the corresponding reference spectrum.
- `wavelength` is a column vector of wavelengths in nanometres.
- `data` is a column vector of the corresponding values. These will generally be uncalibrated digital numbers. For ASD spectrometers running in white reflectance mode these values will be reflectances in the range 0–1.

It is straightforward to add additional information to existing structures if desired. For example, to add a light reading (in lux) to an existing structure:

```
s.lux = 15000
```

A new field called `lux` would then be automatically added.

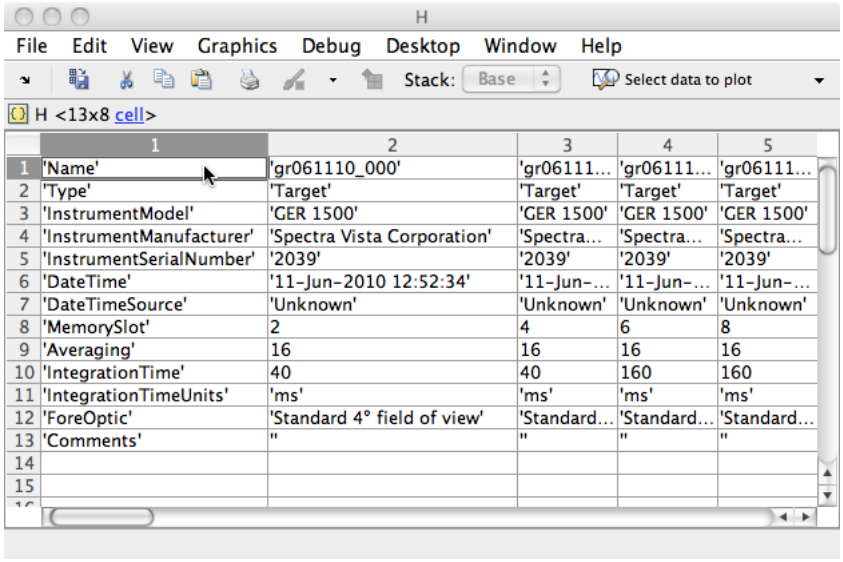
Further information on structure arrays is available in the MATLAB documentation.

3.2.2. Workspace browser

Once imported the spectra can be examined in the workspace browser. This can be opened by selecting WORKSPACE from the DESKTOP menu, or type the command `workspace`. The spectra will be visible as structure arrays with the names given when imported. Double-click an array to browse its contents. If the strucure contains multiple spectra, they will be listed as a row vector. Double-click again examine a specific spectrum.

More information on using the workspace browser is available in the MATLAB documentation.

[3] The source of this data may be the spectrometer's internal clock, or may be the clock of the computer or PDA used to record the spectrum.



	1	2	3	4	5
1	'Name'	'gr061110_000'	'gr06111...	'gr06111...	'gr06111...
2	'Type'	'Target'	'Target'	'Target'	'Target'
3	'InstrumentModel'	'GER 1500'	'GER 1500'	'GER 1500'	'GER 1500'
4	'InstrumentManufacturer'	'Spectra Vista Corporation'	'Spectra...	'Spectra...	'Spectra...
5	'InstrumentSerialNumber'	'2039'	'2039'	'2039'	'2039'
6	'DateTime'	'11-Jun-2010 12:52:34'	'11-Jun-...	'11-Jun-...	'11-Jun-...
7	'DateTimeSource'	'Unknown'	'Unknown'	'Unknown'	'Unknown'
8	'MemorySlot'	2	4	6	8
9	'Averaging'	16	16	16	16
10	'IntegrationTime'	40	40	160	160
11	'IntegrationTimeUnits'	'ms'	'ms'	'ms'	'ms'
12	'ForeOptic'	'Standard 4° field of view'	'Standard...	'Standard...	'Standard...
13	'Comments'	''	''	''	''
14					
15					

Figure 3: Use the `headers` function to combine all headers into a single table.

3.2.3. Comma-separated lists

A specific field of a structure array can be accessed as a comma-separated list. For example, if `s` is a structure array of spectra, typing:

```
s.name
```

produces a comma-separated list of the names of all the spectra:

```
ans =
gr061110_000_reference

ans =
gr061110_001_reference

...
```

Comma-separated lists can easily be assigned to variables. To store the above list in a variable called `allnames` type:

```
allnames = {s.name}
```

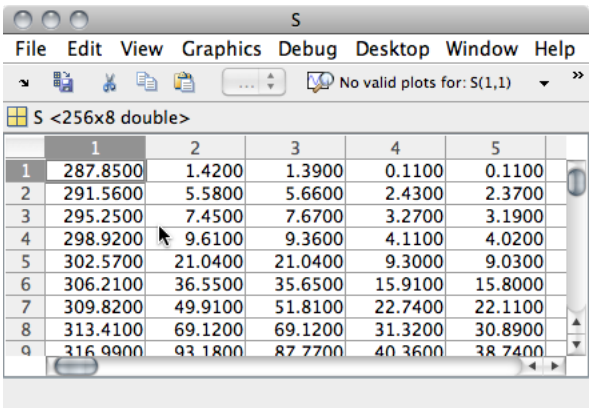
The curly brackets (`{}`) in concatenate the list into a cell array.

Using comma-separated lists provides a way to rearrange imported data in any format or structure that may be required. It is particularly useful when dealing with a large number of spectra as described in the following subsections. Further information about and examples of comma-separated lists are available in the MATLAB documentation.

3.2.4. Creating a table of header information

When a large number of spectra have been imported it may be convenient to summarize all header information in a single table, as shown in Figure 3. The `headers` function provides a convenient way to produce a cell array containg the values of all the header fields.

To create a cell array of header information `H` from a structure array `s`, type:



	1	2	3	4	5
1	287.8500	1.4200	1.3900	0.1100	0.1100
2	291.5600	5.5800	5.6600	2.4300	2.3700
3	295.2500	7.4500	7.6700	3.2700	3.1900
4	298.9200	9.6100	9.3600	4.1100	4.0200
5	302.5700	21.0400	21.0400	9.3000	9.0300
6	306.2100	36.5500	35.6500	15.9100	15.8000
7	309.8200	49.9100	51.8100	22.7400	22.1100
8	313.4100	69.1200	69.1200	31.3200	30.8900
9	316.9900	93.1800	87.7700	40.3600	38.7400

Figure 4: Data can be copied into a single matrix if required.

```
H = headers(s)
```

This table can then be viewed variable editor by typing:

```
openvar H
```

or selecting the variable `H` in the WORKSPACE BROWSER. The header information is presented in columns with the first column displaying the header field names, as illustrated in Figure 3.

3.2.5. Formatting data as a single numeric array

Spectrum data readily be copied into a single matrix by typing:

```
A = [s.data]
```

The square brackets ([]) in this expression concatenate the numeric values in the `data` field into a single matrix `A`. The matrix will contain all the spectral data arranged in columns.

Usually, all spectra in a structure array will have the same wavelength scale. If this is the case, the vector of wavelengths can be copied into a separate variable, say `w`, by typing:

```
w = s(1).wavelength
```

Alternatively, it is often convenient to arrange both wavelength values and the spectrum data in a single matrix with wavelengths in the first column and data in subsequent columns as illustrated in Figure 4. This can be done by typing:

```
B = [s(1).wavelength, [s.data]]
```

The matrix can then be opened in the variable editor by typing:

```
openvar B
```

Or selecting the variable `B` in the WORKSPACE BROWSER. Note that when arranging the data in this way the data for first spectrum will be in column 2; the data for the second will be in column 3, etc.

3.3. Plotting

MATLAB provides all the functions required to produce publication-quality plots of field spectra. A single spectrum stored in a structure, e.g. `s`, can be plotted by typing:

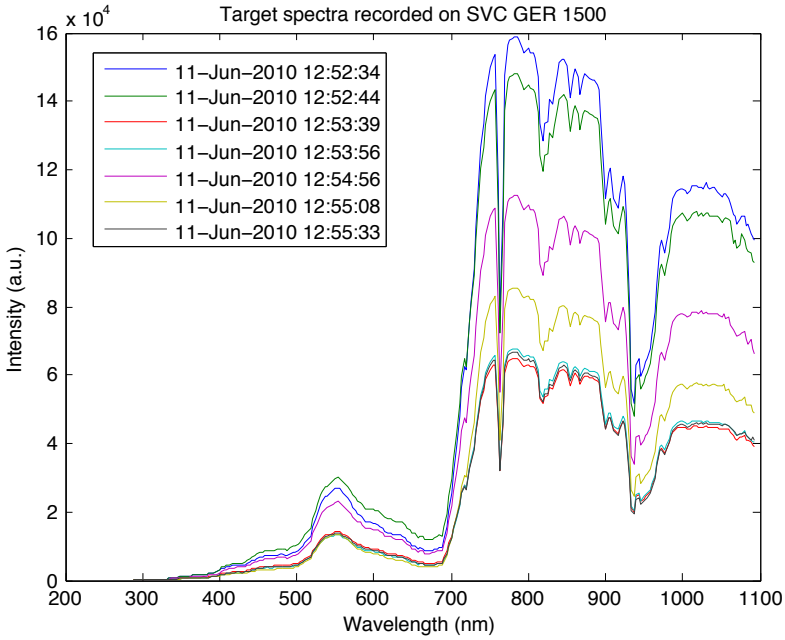


Figure 5: Plot of seven target spectra from a SVC GER 1500 spectroradiometer.

```
plot(s.wavelength, s.data)
```

This plots the data values vertically against their corresponding wavelengths.

To plot a structure array of multiple spectra type:

```
plot([s.wavelength], [s.data]).
```

The square bracekts (`[]`) in this expression concatenate the `wavelength` and `data` fields into two separate matricies.

To plot an individual spectrum, say the sixth, from a structure array `s` type:

```
plot(s(6).wavelength, s(6).data)
```

To plot a range of spectra, say the fourth to the sixth (inclusive), type:

```
plot([s(4:6).wavelength], [s(4:6).data])
```

When plotting reflectance data, it may be preferable to multiply the data values by 100 to produce a reflectance plot in per cent:

```
plot([s.wavelength], 100*[s.data])
ylabel('Reflectance %')
```

The wavelength values are usually in nanometres (nm). To produce a plot in micrometres (μm) type:

```
plot(0.001*[s.wavelength], [s.data])
```

A legend can be added to the graph using MATLAB's `legend` function. For example, to add a legend showing the name of each spectrum type:

```
legend(s.name)
```

Axis labels, ranges, and titles can be added using MATLAB's built-in comands or in the PLOT EDITOR. For example, the plot of target spectra shown in Figure 5 was produced by typing:

```
plot([tar.wavelength], [tar.data]);
legend(tar.name);
xlabel('Wavelength (nm)');
ylabel('Counts (DN)');
title('Target spectra recorded on SVC GER 1500');
```

See overview of plotting in the MATLAB documentation for more ways to customize plots.

4. Processing functions

This section describes some of the processing functions in the toolbox required to process the imported data and produce reflectance spectra.

4.1. Pairing target and reference spectra

This process is usually only required when data have been recorded in *raw mode* on an ASD spectroradiometer. In order to calculate reflectance spectra the (raw) target and reference spectra must be paired so that each target spectrum has a corresponding reference spectrum. Once this is done reflectance can be calculated by dividing the two spectra using the `relativereflectance` function described in Section 4.3. For SVC spectroradiometers the `pair` function as the instrument keeps track of target and reference spectra using the target/reference button(s).

The information required to pair target and reference spectra is usually recorded in the field on a logsheet. This information must be imported into MATLAB to pair up the spectra. To do this the names of the spectra are copied into a text file in the comma-separated values (CSV) format. An example is shown in Figure 2 and included in the `examples` folder. Each line of the text file gives the name of one target spectrum followed by the name of its corresponding reference spectrum.

> Logsheets for all of the Field Spectroscopy Facility's instruments can be downloaded as PDF files.

To pair up target and reference spectra, first import all the spectra into MATLAB by typing:

```
s = importasd('*.txt')
```

Then use the pair function to separate and pair target and reference spectra. For example, if the logsheeet is in a file in the current folder called `logsheet.csv` type:

```
[tar, ref] = pair(s, 'logsheet.csv')
```

If output is not suppressed, this displays:

```
tar =

1x17 struct array with fields:

    name
    datetime
    header
    wavelength
    data
    pair
```

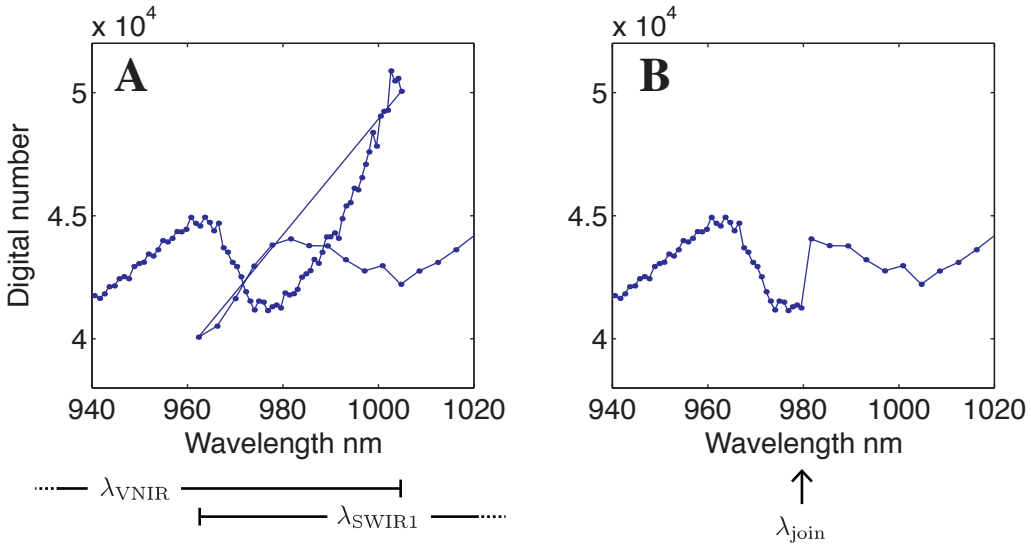


Figure 6: A small region of a spectrum recorded on an SVC HR-1024 spectroradiometer showing overlapped data (A). The VNIR detector records wavelengths up to 1005 nm whilst the SWIR1 detector starts at 962 nm. When the spectra are joined (B) at 980 nm a sharp jump in the intensity occurs.

```
ref =

1x4 struct array with fields:

    name
    datetime
    header
    wavelength
    data
```

This separates the target and reference spectra into two separate structure arrays called `tar` and `ref`. Note that the `tar` structure array has a field called `pair` which gives the name of the paired spectrum. This field is used by the `relativereflectance` function to calculate reflectance spectra (see Section 4.3.

4.2. Removing overlapped data

Spectroradiometers that cover both the visible near infared (VNIR) and short wave infared (SWIR) spectral regions have multiple detectors. For example the SVC HR-1024 has a silicon (Si) array detector for the VNIR spectral region and two indium gallium arsenide (InGaAs) array detectors for the SWIR region. There is a small area of overlap around the long wave edge of the Si VNIR detector and the short wave edge of the first InGaAs SWIR detector (SWIR1). This overlap region is typically in the range $960 - -1050$ nm. Figure 6(A) shows the overlap region in a field spectrum. The overlapped data can cause problems for processing and must usually be removed prior to any further processing.

On ASD spectroradiometers the overlapped region is removed automatically by the operating software, therefore ASD spectra will never contain overlapped data. On the SVC HR1024 the overlapped data may be *removed* or *preserved* depending on the OVERLAP/MATCHING settings chosen in the SVC operating software (accessed through the

SETUP menu)[4]. The Facility recommends setting this option to *preserve* and removing the overlap during post processing.

A function called `removeoverlap` is provided in the toolbox to join the VNIR and SWIR1 regions at a specified join wavelength. For example, to remove overlap from target and reference spectra type by joining the two regions at 980 nm type:

```
tar_joined = removeoverlap(tar, 980)
ref_joined = removeoverlap(ref, 980)
```

After joining the spectra there is usually a sharp jump in the spectral data value either side of the join wavelength. Figure 6(B) shows an example of a spectrum with overlap removed. This toolbox does not at present provide any 'matching algorithms' to remove this feature.

Note that removing overlapped data changes the set of wavelength values in the spectrum. The joined spectra will therefore have a different wavelength scale.

4.3. Relative reflectance

Spectral relative reflectance $R_{\mathrm{rel}}(\lambda)$ as a function of wavelength λ is defined as the ratio of the target spectrum $L(\lambda)$ to the corresponding relative reference spectrum $E_{rel}(\lambda)$

$$R_{rel}(\lambda) = \frac{L(\lambda)}{E_{rel}(\lambda)}$$

The relative reflectance spectrum is usually measured in the field by recording a spectrum of the light reflected from a reference panel.

The function `relativereflectance` calculates relative reflectance spectra by dividing each target spectrum by its corresponding reference spectrum. If `tar` and `ref` are structure arrays of paired target and reference spectra, typing:

```
R_rel = relativereflectance(tar, ref)
```

calculates relative reflectance spectra. The information about which target spectrum should be paired with which reference spectrum is contained in the `pair` field of the target spectra. Section 4.1 describes how to pair spectra. Note that the number of reflectance spectra will equal the number of target spectra.

4.4. Absolute reflectance

Absolute spectral reflectance $R_{abs}(\lambda)$ as a function of wavelength λ is the ratio of the target spectrum $L(\lambda)$ to the spectral irradiance $E(\lambda)$

$$R_{\mathrm{abs}}(\lambda) = \frac{L(\lambda)}{E(\lambda)}$$

Generally in field spectroscopy $E(\lambda)$ is not measured directly, but instead a spectrum of the irradiance reflected from a reference panel is recorded. What is measured therefore

[4] The software used to record spectra on a handheld device (PDA) does not have overlap/matching settings and preserves overlap by default.

is the relative irradiance, $E_{\text{rel}}(\lambda)$. This is the spectral irradiance $E(\lambda)$ multiplied by the spectral reflectance of the panel $R_{\text{panel}}(\lambda)$

$$E_{\text{rel}}(\lambda) = R_{\text{panel}}(\lambda)E(\lambda)$$

If $R_{\text{panel}}(\lambda)$ is known, then absolute reflectance can be calculated from the measured relative reflectance

$$R_{abs}(\lambda) = \frac{L(\lambda)}{E(\lambda)} = \frac{R_{\text{panel}}(\lambda)L(\lambda)}{E_{\text{rel}}(\lambda)} = R_{\text{panel}}(\lambda)R_{\text{rel}}(\lambda)$$

Therefore to convert a measurement of relative reflectance to absolute reflectance the spectrum must be multiplied by the reflectance of the panel that was used to record it. The panel's reflectance spectrum, $R_{\text{panel}}(\lambda)$, can be measured in the laboratory as a calibration procedure and the calibration data then applied to field spectra in post processing.

> Calibration data for the all Field Spectroscopy Facility's reference panels are available in an Excel spreadsheet.

A reference panel calibration spectrum $R_{panel}(\lambda)$ can be imported into MATLAB using the `importpanelcal` function. Two file types are supported:

1. A comma-separated values (CSV) file with a header which gives information about the panel's calibration
2. An Excel spreadsheet provided by the Field Spectroscopy Facility

An example of a panel calibration file in CSV format is shown in Figure 7. This file can be used as a template for panel calibration data if required. The header must contain the panel's name. This should be a unique name or serial number which identifies which panel the calibration refers to. The date and time at which the calibration was performed must also be included in the header.

To import a panel calibration file in CSV format into MATLAB type:

```
p = importpanelcal('panel.csv')
```

Alternatively, panel calibration data may be imported from an Excel spreadsheet provided by the Field Spectroscopy Facility. As the spreadsheet contains data for all the Facility's panels, the serial number of the panel to be imported must be specified:

```
P = importpanelcal('FSF Ref Panel Cal Data 2010_1.xls', 'SRT #008')
```

> MATLAB will issue a warning when importing data from the FSF's Excel spreadsheet to indicate that the xlsread function has limited import functionality in basic mode. This warning may be safely ignored.

The panel calibration spectrum can be plotted by typing:

```
plot(p.wavelength, 100*p.data)
xlabel('Wavelength nm')
ylabel('Panel reflectance %')
```

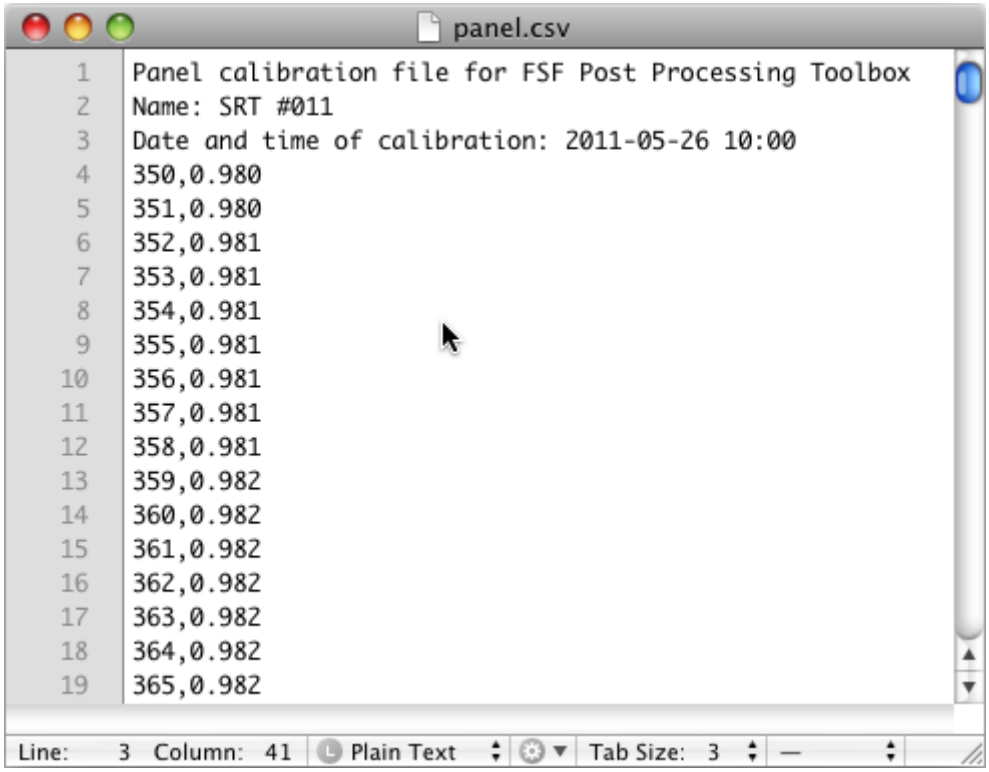


Figure 7: A example of a CSV file containing a reference panel calibration spectrum. A copy of this file can be found in the `examples` folder. It can be imported into MATLAB with the `importpanelcal` function. The data consist of wavelengths in nm and the corresponding panel reflectance as a number in the range 0–1.

The reflectance values were multiplied by 100 to convert them to per cent.

A structure array of absolute reflectance spectra can be calculated from a structure array of relative reflectance spectra `R_rel` and a structure containg the panel calibration data by typing:

```
R_abs = absolutereflectance(R_rel, P)
```

If the panel calibration spectrum was recorded with the same spectrometer as the field spectrum then both will have the same the set of wavelength values (λ). If they were recorded on different instruments the panel spectrum will be interpolated to the wavelengths of the relative reflectance spectrum.

Once calculated, the absolute reflectance spectra can be plotted by typing:

```
plot([R_abs.wavelength], 100*[R_abs.data]);
legend(R_abs.name);
xlabel('Wavelength (nm)');
ylabel('Absolute reflectance (%)');
title('Reflectance spectra recorded on SVC GER 1500');
```

4.5. Smoothing

Spectra can be smoothed with a Savitzky–Golay filter [6] by typing:

```
s_smoothed = sgsmooth(s)
```

This smooths all spectra in the structure array `s`, returning a structure array of smoothed spectra `s_smoothed`.

Note that the smoothing operation reduces the wavelength range of the spectra. The smoothed spectra will therefore have a different set of wavelength values than the original.

The function `sgsmooth` makes use of MATLAB's `sgolay` function to design the filter. This function is part of MATLAB's Signal Processing Toolbox. Further information can be found in the documentation for `sgolay`.

4.6. Removing water bands

The solar irradiance reaching the ground can be very low in some spectral regions due to water absorption. The table below gives two spectral regions where water absorption is particularly high.

	Start wavelength	End wavelength
Water band 1	1350 nm	1460 nm
Water band 2	1790 nm	1960 nm

The high absorption of water results in a very low irradiance $E(\lambda)$ at ground. As reflection is divided by irradiance

$$R_{\text{abs}}(\lambda) = \frac{L(\lambda)}{E(\lambda)}$$

the errors transmitted to the absolute reflectance can become very large. This manifests as noisy regions in spectra. These regions are often ommited from plots.

The function removewater deletes the data points in the above water band regions. Type

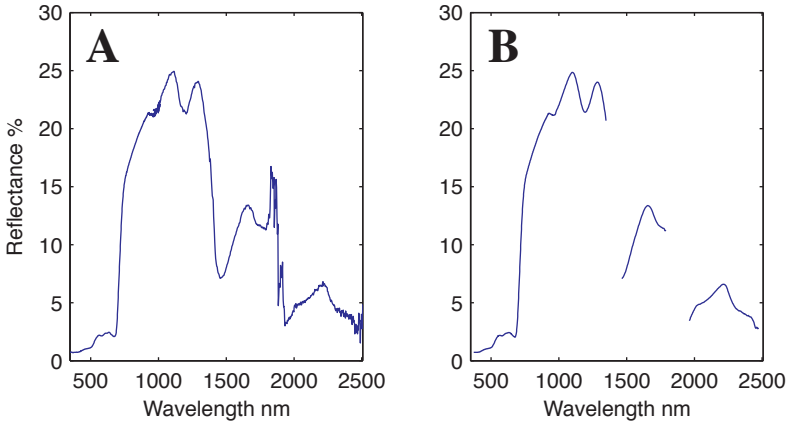


Figure 8: Example of post processing. The original spectrum (A) contains overlapped data which were removed with the `removeoverlap` function. The join wavelength was 980 nm. The spectrum was then smoothed with the `sgsmooth` function. The water bands were removed with `removewater`, resulting in the output spectrum (B).

```
s_nowater = removewater(s)
```

to delete the water bands regions from the structure array `s`, returning a new structure array `s_nowater`. The data points are removed by replacing them with the special value *Not a Number* (NaN). This value is commonly used for undefined or unrepresentable numbers. A more detailed description of NaN is given in the MATLAB documentation.

Figure 8 shows an example of water band removal.

5. Radiometric calibration

For instruments that have been calibrated this section describes how to apply the calibration data to convert reference and target spectra to radiometric (SI) units.

5.1. Introduction

Absolute spectral measurements are those expressed in SI derived units. A calibrated field spectroradiometer can make measure two key radiometric quantities: spectral radiance and spectral irradiance. As spectral quantities both are functions of wavelength λ. The conventional SI units for these quantities are given in the table below:

Quantity	Symbol	Units	Calibration standard (typical)
Radiance	$L(\lambda)$	$\mathrm{Wsr^{-1}m^{-2}nm^{-1}}$	FEL lamp
Irradiance	$E(\lambda)$	$\mathrm{Wm^{-3}nm^{-1}}$	Integrating sphere lamp

To make absolute measurements the spectroradiometer must first be calibrated, a process usually performed in the laboratory using a calibrated light source.

All spectrometers measure a spectrum in digital numbers (DN), which must then be converted to the appropriate radiometric quantity by multiplying the spectrum by the system response for that radiometric quantity[5]. The system response measures the signal level

[5]The system response is also known as the calibration gain.

at each wavelength to a known source of radiance or irradiance. It depends on many aspects of the spectroradiometer: the elements in the optical pathway, the properties of the detectors and the choice fore-optic. For this reason each calibration is specific to a certain configuration of the spectroradiometer. It must be performed again whenever the configuration is changed.

5.2. Radiance

Spectral radiance can be calculated by multiplying a measured field spectrum $S(\lambda)$ in digital numbers (DN) by the system response to radiance $C_L(\lambda)$

$$L(\lambda) = C_L(\lambda)S(\lambda)$$

If $C_L(\lambda)$ is measured in a calibration procedure then any spectrum subsequently recorded on the same spectroradiometer (in the same configuration) can be expressed as absolute radiance $L(\lambda)$ in SI units.

To find $C_L(\lambda)$ a calibration spectrum $S_{\text{cal}}(\lambda)$ is recorded in a carefully-controlled laboratory setup using a calibrated standard of known radiance $L_{\text{standard}}(\lambda)$ as the light source

$$L_{\text{standard}}(\lambda) = C_L(\lambda)S_{\text{cal}}(\lambda)$$

This equation can be rearranged to find the system repsonse to radiance $C_L(\lambda)$

$$C_L(\lambda) = \frac{L_{\text{standard}}(\lambda)}{S_{\text{cal}}(\lambda)}$$

5.3. Irradiance

Similarly for irradiance, a spectrum can be converted to radiometric units by multiplying it by the system response to irradiance

$$E(\lambda) = C_E(\lambda)S(\lambda)$$

Using a known source of irradiance $E_{\text{standard}}(\lambda)$ the system response to irradiance can be found

$$C_E(\lambda) = \frac{E_{\text{standard}}(\lambda)}{S_{cal}(\lambda)}$$

5.4. Importing the system response into MATLAB

Before calculating radiometric spectra the appropriate system response measurements must be imported into MATLAB using the `importradcal` function.

The `importradcal` function reads calibration data in an XML file format. An example file in this XML format is provided in the `examples` folder. This folder is located in the `FSFPostProcessing1.3.6` folder at the location where the toolbox was installed. A template for Microsoft Excel is also provided to read and write files in this format. The template can be found in the `excel` folder.

> Radiometric calibration data for calibrations performed at the Field Spectroscopy Facility are available in an Excel spreadsheet. MATLAB cannot import this spreadsheet directly. The data set for the instrument used must exported to an XML file using the provided Excel template.

To import a radiometric calibration XML file

```
C_L = importradcal('radcalexample.xml')
```

The data file is imported into a structure array. If output is not suppressed (with a semi-colon at the end of the line) then the structure is displayed

```
C_L =

    name:  'FSF radiance calibration example'
    datetime:  '27-Oct-2009 12:00:00'
    header:  [1x1 struct]
    wavelength:  [2151x1 double]
    data:  [2151x1 double]
```

The `wavelength` and `data` fields give the system response measurement at each wavelength. The `header` field provides additional information (imported from the XML file) about the calibration such as the instrument's serial number and the calibration standard which was used to measure the system response.

5.5. Calculating radiance and irradiance

If `S` is a structure array of target field spectra and `C_L` is the system response imported with the `importradcal` function then radiance can be calculated by typing:

```
L = radiance(S, C_L)
```

Similarly, if S is a structure array of reference field spectra and `C_E` is the system response to irradiance then irradiance can be calculated by typing:

```
E = irradiance(S, C_E)
```

> Although the radiance and irradiance functions perform exactly the same calculation they should be applied to different types of spectra and give results in different units.

6. Comparison with airborne and satellite instruments

This section describes the `convolve` function which can be used to reduce the spectral resolution of field spectra to match the bands of a airborne or satellite instrument. A `Band` class is also introduced which provides a convenient way to load, store and plot the spectral response functions of these instruments in MATLAB.

6.1. Introduction

The need often arises to compare field spectra with spectra recorded by airborne or satellite spectroscopic instruments such as imaging spectrometers. These instruments typically have poorer (or much poorer) spectral resolution than field spectrometers and will therefore provide less detailed spectra. In order to make a sensible comparison the spectral resolution of the field spectra must be reduced to match the spectral response functions (bands) of the airborne or satellite instruments. This is done by convolving the field spectra with the response functions.

The types of instruments fall into two broad classes: multispectral imagers and imaging spectrometers[6]. The convolution process is different for the two instrument types and will be described in separate subsections.

6.2. Multispectral instruments

The spectral response function of an instrument describes the spectrum produced by the detector in response to a purely monochromatic light source at a wavelength λ_{source} [7].

Multispectral sensors make measurements of light 'intensity' in a number different bands. The spectral response function of each band therefore describes the response of the band's detector to monochromatic light at wavelength λ_{source}. For an instrument with N bands, the response of band n to a monochromatic light source at wavelength λ_{source} is given by a function $f_n(\lambda_{\text{source}})$. As each band has its own spectral response function, there will be a set of such functions

$$f_1(\lambda_{\text{source}}), f_2(\lambda_{\text{source}}), ..., f_N(\lambda_{\text{source}})$$

In general it is not important to know the absolute spectral response of an instrument and the relative spectral response is sufficient. The functions are therefore normalized to unit area

$$\int_0^\infty f_n(\lambda)\mathrm{d}\lambda = 1 \text{ for all } n$$

If the source spectrum $S_{\text{source}}(\lambda)$ were known—which it generally isn't—the total response in band n could be found by integrating the product of the source spectrum and the spectral response function over the full range of wavelengths λ

$$S_n = \int_0^\infty S_{\text{source}}(\lambda) f_n(\lambda)\mathrm{d}\lambda$$

Often it is required to calculate the relative band responses that would be generated if a known field spectrum were detected by a multiband detector. In this scenario the high-resolution field spectrum can be assumed to be identical with the source spectrum and substituted for it in the above equation to give

$$S_n = \int_0^\infty S_{field}(\lambda) f_n(\lambda)\mathrm{d}\lambda$$

[6] Imaging spectrometers are also known as hyperspectral instruments.

The set of spectral response functions $f_n(\lambda_{\text{source}})$ is typically measured as part of the instrument's calibration. Armed with this measurement, and the field spectrum $S_{\text{field}}(\lambda)$, the above integral can be calculated. The discrete measurements are multiplied (interpolating if necessary) and the integral is performed with an approximation method such as the trapezoidal rule.

It is common to label the bands not by their index n, but by their centre wavelengths λ_c.

6.3. Spectrometers

A spectrometer has a set of closely-spaced spectral response functions which depend on the source wavelength λ_{source}. The response of the instrument at detector wavelength λ to a purely monochromatic light source at wavelength λ_{source} has the functional form

$$f = f(\lambda, \lambda_{\text{source}})$$

It is common to assume—and usually the case [7]—that the shape of f changes only slightly with source wavelength. It can therefore be expressed as a single function shifted to the source wavelength

$$f = f(\lambda - \lambda_{\text{source}})$$

Again, the spectral response function is generally normalized such that

$$\int_{-\infty}^{\infty} f(\lambda)\mathrm{d}\lambda = 1$$

The detected spectrum is the response at detector wavelength λ due to light from all parts of the source spectrum is found by integrating over all the source wavelengths

$$S(\lambda) = \int_0^{\infty} S_{\text{source}}(\lambda_{\text{source}}) f(\lambda - \lambda_{\text{source}})\mathrm{d}\lambda_{\text{source}}$$

This integral is the convolution of the source spectrum with the spectral response function. The result is the detected spectrum as a function of wavelength $S(\lambda)$.

Ideally the spectral response function of every instrument would be measured. In practice this may not be possible and a variety of methods have been developed to approximate it [8]. These generally involve approximating the spectral response functions as a series of Gaussian functions whose widths and centre wavelengths are set up to match the instrument's specifications.

6.4. Reducing the spectral resolution

For comparing spectra of high resolution (HR) ground-based field spectrometers with the comparitavely lower resolution (LR) airborne or satellite instruments the HR data must be reduced in resolution to the LR instrument. In other words we wish to know how a particular spectrum acquired on the ground would appear if it had been detected with a lower resolution instrument. This question can be answered by convolving the source spectrum with the spectral response function of the LR instrument

$$S_{LR}(\lambda) = \int_0^{\infty} S_{\text{source}}(\lambda_{\text{source}}) f_{LR}(\lambda - \lambda_{\text{source}})\mathrm{d}\lambda_{\text{source}}$$

Unfortunately the source spectrum is not usually known. However, if the HR instrument has a spectral resolution significantly higher than the LR instrument, its spectral response funciton may be sufficiently narrow that the source spectrum can be approximated by the HR spectrum

$$S_{HR}(\lambda) \approx S_{\text{source}}(\lambda)$$

Substituting into the above equation

$$S_{LR}(\lambda) = \int_0^\infty S_{HR}(\lambda_{\text{source}}) f_{LR}(\lambda - \lambda_{\text{source}}) \mathrm{d}\lambda_{\text{source}}$$

If f_{LR} is known or modelled then this convolution can be performed numerically.

6.5. In MATLAB

The function `convolve` provides a means to convolve a spectrum or spectra with the spectral response functions of a specific airborne or satellite instruments. The first step in this processing function is to download the spectral response functions (bands) for the specific instrument. A MATLAB class called `Band` is provided to facilitate handling these data. A class works in a very similar way to a structure array, however classes can also contain methods. An introduction to classes is given in the MATLAB documentation.

A selction of band data for various instruments is available from the Field Spectroscopy Facility's web site.

These data are provided as XML files and are listed on the Field Spectroscopy Facility's web site.

The class `Band` can be used to load response data into MATLAB. For example, to load spectral response data for the POLDER instrument type

```
POLDER = Band('http://fsf.nerc.ac.uk/user_group/bands/POLDER.xml')
```

This loads the data into MATLAB and stores it in an object called `POLDER`. To plot the bands type:

```
POLDER.plot
```

By default the spectral response functions are are normalized to unit area. The `normalizeHeight` method can be used to normalize such that the height of each response function is 1:

```
POLDER.normalizeHeight.plot
```

To convolve a field spectrum in a structure array `S` with the spectral bands, type

```
t = convolve(s, POLDER)
```

If the spectrum `S` and the bands `POLDER` are defined on different wavelength scales, the bands will be interpolated. The colvolved spectra will be output in a structure array `t`.

If the band centre wavelengths have been defined the output spectrum can be plotted by typing:

```
plot(t.wavelength, t.data)
```

6.6. Feature depth estimation

The depth of an absorption feature in a spectrum can be estimated using the method described by Clark and Roush [9]. The function `featuredepth` provides an illustration of the method. If `s` is a spectrum, the depth of an absorption feature between wavelengths `w1` and `w2` can be estimated by typing:

```
[wf, depth] = featuredepth(s, w1, w2)
```

The output `wf` gives the wavelength of the feature. The funciton also plots an illustration of the process used to estimate the depth.

References

[1] Milton, Edward J., "Progress in field spectroscopy," *Remote Sensing of Environment*, volume 113, pp. S92–S109, 2009

[2] Spectra Vista Corporation, *HR-1024 User Manual*, 1.5 edition, 2008

[3] MacLellan, Chris J. and Malthus, Tim J., "High performance dual field of view spectroradiometer with novel input optics for autonomous reflectance measurements over an extended spectral range," *IGARSS*, 2009

[4] Robinson, Iain and MacLellan, Chris J., "A dual field of view spectroradiometer for near-simultaneous measurement of irradiance and reflected radiance," , 2011

[5] MacLellan, C., *V–SWIR data file format and remote control command set*, Field Spectroscopy Facility, 7 edition, 2010

[6] Savitzky, Abraham and Golay, M J E, "Smoothing and Differentiation of Data by Simplified Least Squares Procedures." *Analytical Chemistry*, volume 36, no. 8, pp. 1627–1639, 1964

[7] James, J F, *Spectrograph Design Fundamentals*, Cambridge University Press, 2007

[8] Milton, E. J. and Choi, K. Y., "Estimating the spectral response function of the CASI-2," *Proceedings of the Annual Conference of the Remote Sensing and Photogrammetry Society*, 2004

[9] Clark, R N and Roush, T L, "Reflectance spectroscopy: quantitative analysis techniques for remote sensing applications," *J Geophys Res*, volume 89, p. 6329, 1984

A. Normalization of ASD spectra in raw mode

ASD spectra recorded in *raw mode* must be normalized to account for the different responses of the detectors. The normalization is performed during import and the code is contained in the function `ASDFieldSpec`. (Reflectance spectra recorded in *white reference mode* are not normalized.)

The ASD FieldSpec 3 and FieldSpec Pro spectroradiometers have three separate detectors for three different spectral regions. A silicon photodiode array detects light in the visible-near-infrared (VNIR) region. Two InGaAs photodiodes cover two short wave infrared spectral regions labelled SWIR1 and SWIR2.

λ_1 and λ_2 are the join wavelengths. These may be different for different instruments, but the values are saved in ASD spectrum files. They can be found in the `header` structure in fields named `Join1Wavelength` and `Join2Wavelength`.

The pixel values DN are normalized differently in each spectral region:

$$\mathrm{DN}_{\mathrm{norm}}(\lambda) = \begin{cases} \frac{\mathrm{DN}(\lambda)}{T_{\mathrm{VNIR}}} & \lambda \leqslant \lambda_1 \\ \frac{G_{\mathrm{SWIR1}}\mathrm{DN}(\lambda)}{2048} & \lambda_1 < \lambda \leqslant \lambda_2 \\ \frac{G_{\mathrm{SWIR2}}\mathrm{DN}(\lambda)}{2048} & \lambda_2 < \lambda \end{cases}$$

where T_{VNIR} is the integration time of the VNIR photodiode array, G_{SWIR1} is the gain of the SWIR1 photodiode and G_{SWIR2} is the gain of the SWIR2 photodiode. These values are saved in ASD spectrum files, and are imported into the MATLAB workspace as fields in the `header` structure called `VNIRIntegrationTime`, `SWIR1Gain` and `SWIR2Gain` respectively.

B. Using ViewSpec Pro to Convert ASD Binary Files to ASCII

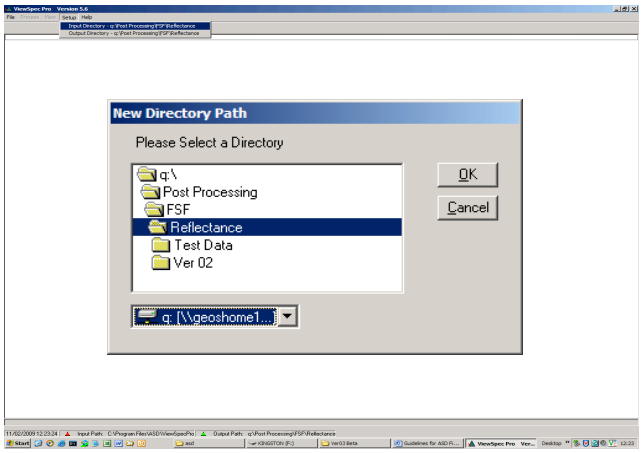
The application ViewSpec Pro from ASD includes many useful features such as graphing, scaling, 1st derivative and conversion of the spectrometer's binary files into ASCII text files. For the purpose of this guideline we will only use the ASCII Export function. The application is installed on each of the facility's computers and is also available for the Analytical Spectral Device's website ftp://ftp.asdi.com/Software/ contact FSF for further details.

- Start the ViewSpec Pro application.

Configuring ViewSpec Pro

The application can save the path/directory to your ASD spectrum files and the converted text files.

- From the Setup menu click on the ***Input Directory*** to select a New Directory Path to your ASD binary data files.



After selecting the default Input Directory you are offered the opportunity to make the ***Output Directory*** match the Input Directory. Alternatively, you can select a different path/directory using the Setup /Output Directory menu.

Open ASD Spectrum (Binary) Files

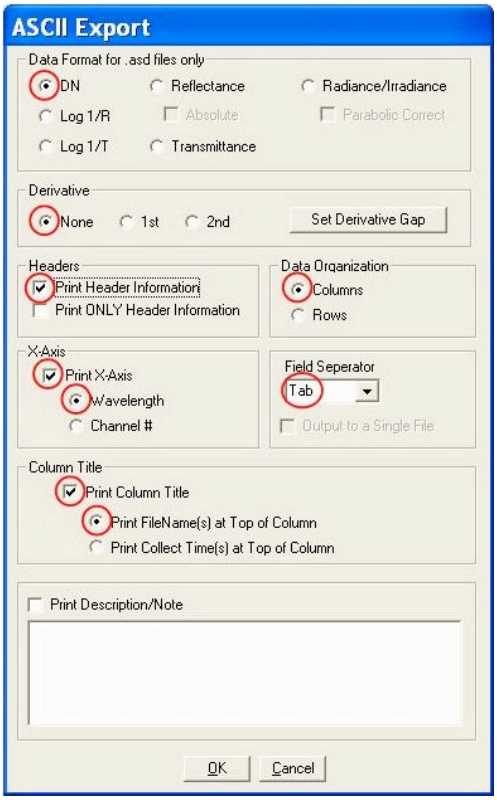
ViewSpec Pro can open and process large numbers of files although graphing is limited to 14 spectra.

- From the *File* menu select *Open* and highlight the ASD White-Ref or radiometric binary files for importation.
- Click Open to bring the files into ViewSpec Pro.

Converting ASD Binary Files to ASCII text

The file list is shown in the application window.

- Highlight each file in the list.
- From the Process menu select ASCII Export.
- Ensure the boxes/buttons circled in red are selected.
- *** NOTE** The new ASD ViewSpec Pro software allows different data formats and derivatives to be selected if required – see the dialogue box below. 'DN' and derivative - 'none' are recommended.
- Click OK to convert the files to ASCII and save them in the Output directory.
- Close the ViewSpec Pro application.



* If using the old version of ViewSpec Pro (4.05) the additional data formats are not available and the box will look like this.